Higgs couplings and properties at CMS and ATLAS

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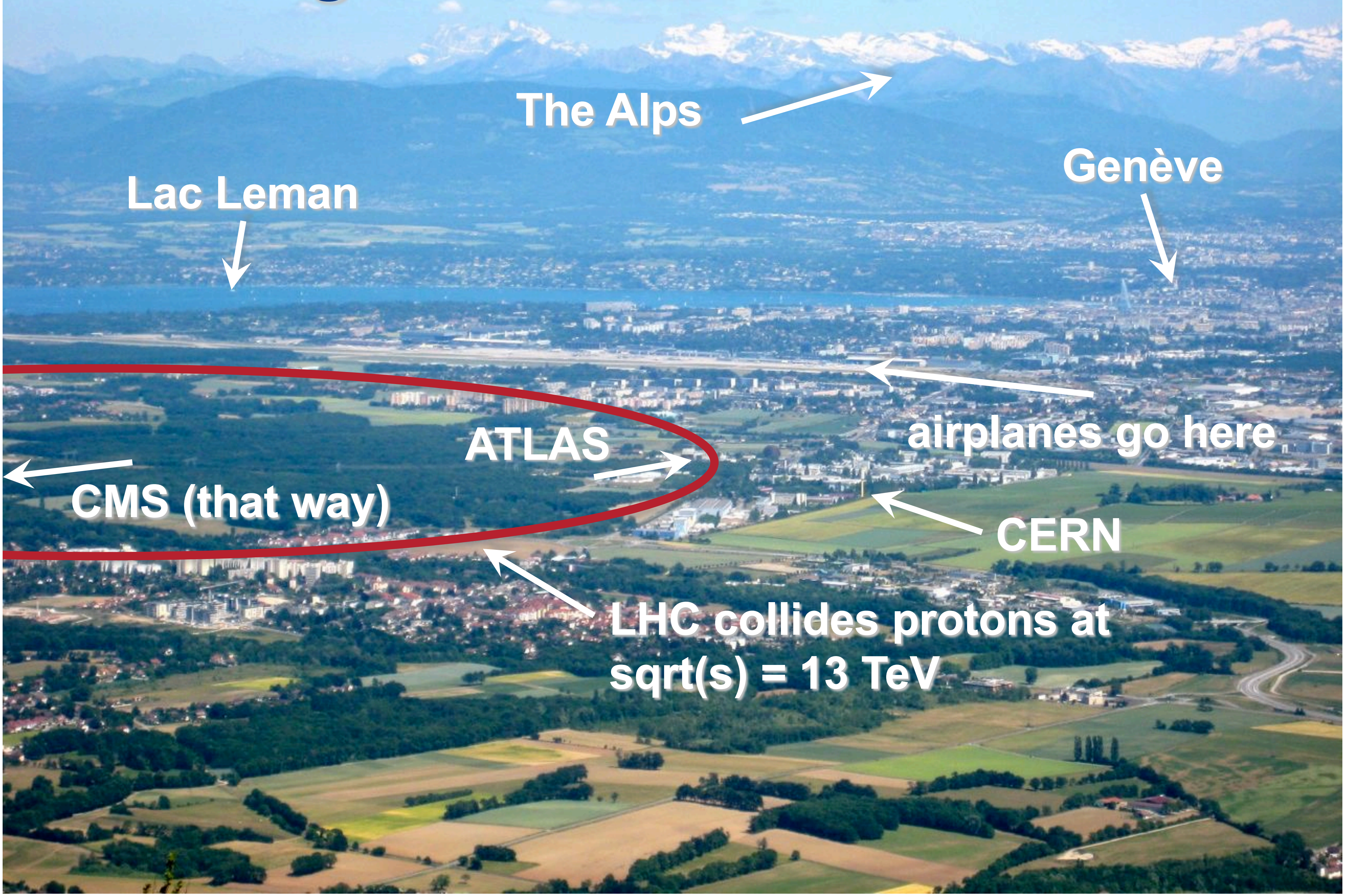
The Standard Model Higgs Boson

Very **specific set of predictions for the Higgs boson in the SM**

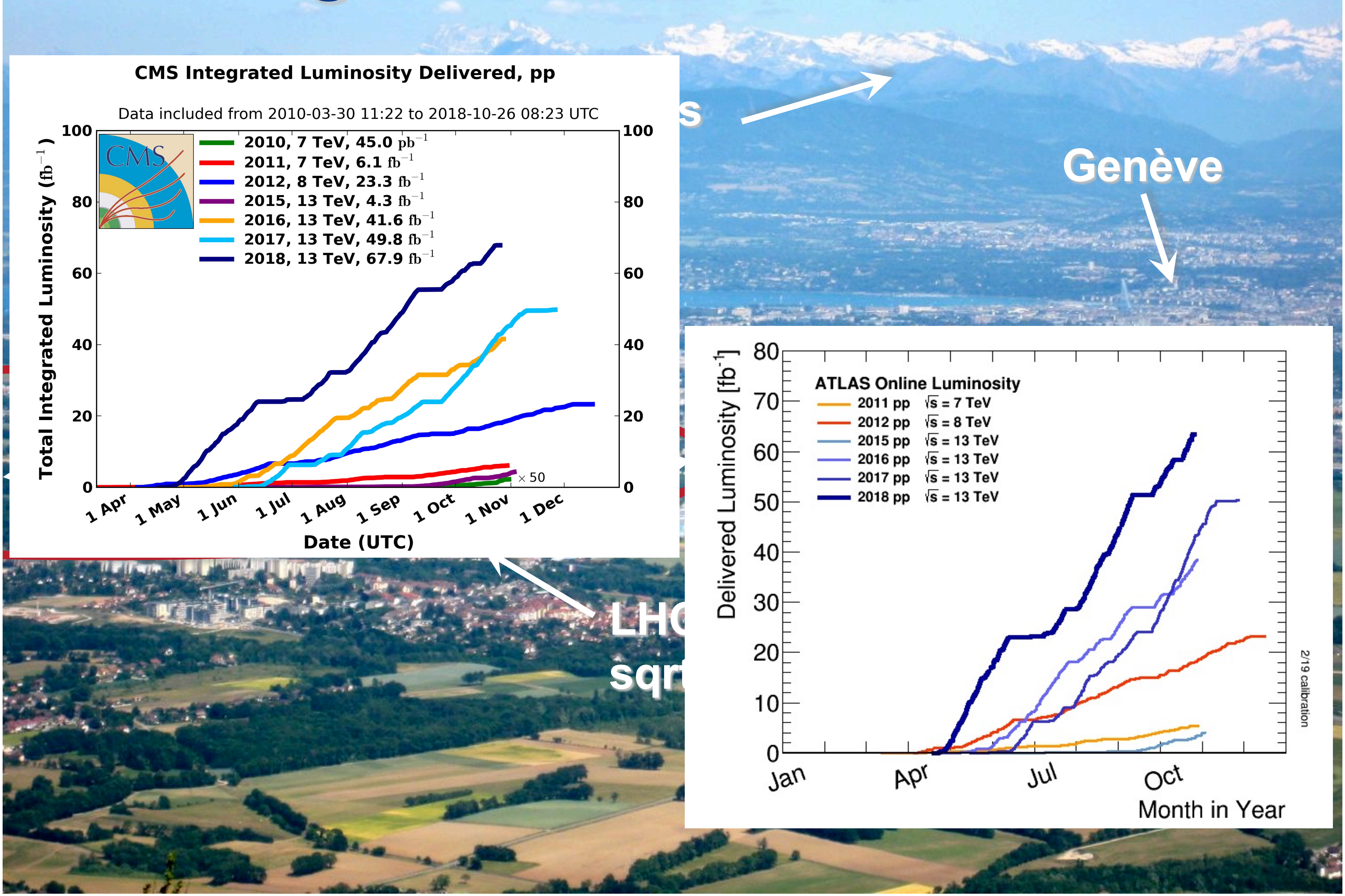
- ✓ Spin-zero scalar
- ✓ **Sole particle** responsible for **electroweak symmetry breaking** (masses of W and Z bosons)
- ✓ Gives mass to all massive elementary particles, **including fermions**
- ✓ Interactions completely determined by 1) the mass of the Higgs boson, 2) the mass of the other particle, and 3) the vacuum expecation value ***v***
- ✓ *Only thing undetermined is the Higgs boson mass* m_H

Predictions of the SM frame our work, even as we search avidly for deviations

The Large Hadron Collider, CERN



The Large Hadron Collider, CERN



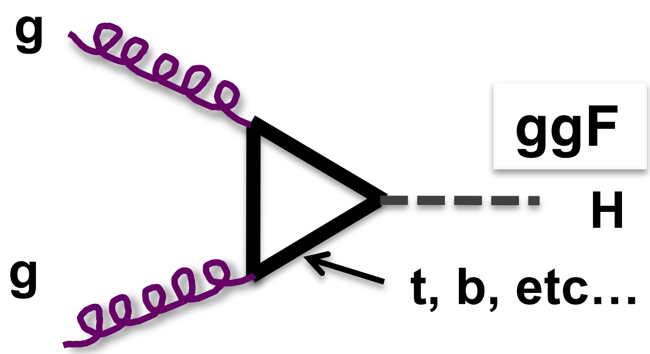
SM Higgs Boson production

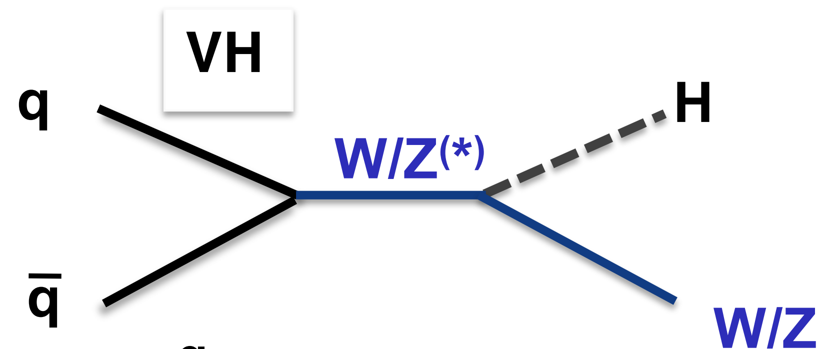
Mediated via heavy particles

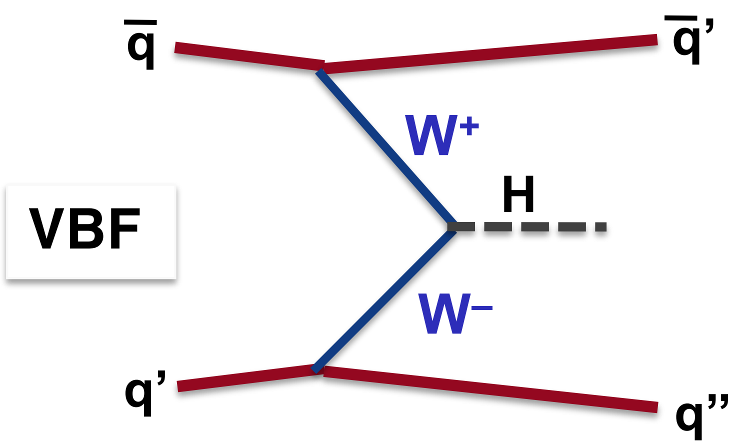
Distinctive final-state features allow "tagging" of events for categorization

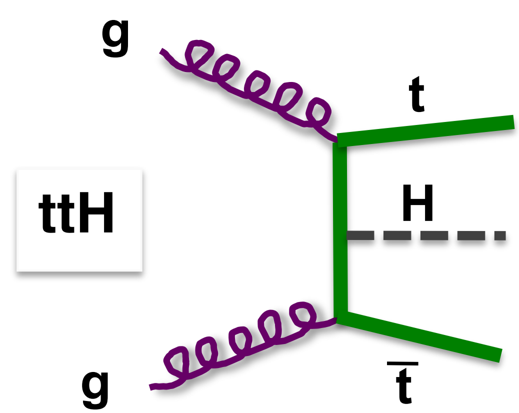
Cross sections for m_H=125 GeV:

	process	13 TeV
ggF	gluon-gluon fusion	49 pb
VBF	vector-boson fusion	3.8 pb
VH	associated production	2.3 pb
ttH	associated production	0.51 pb



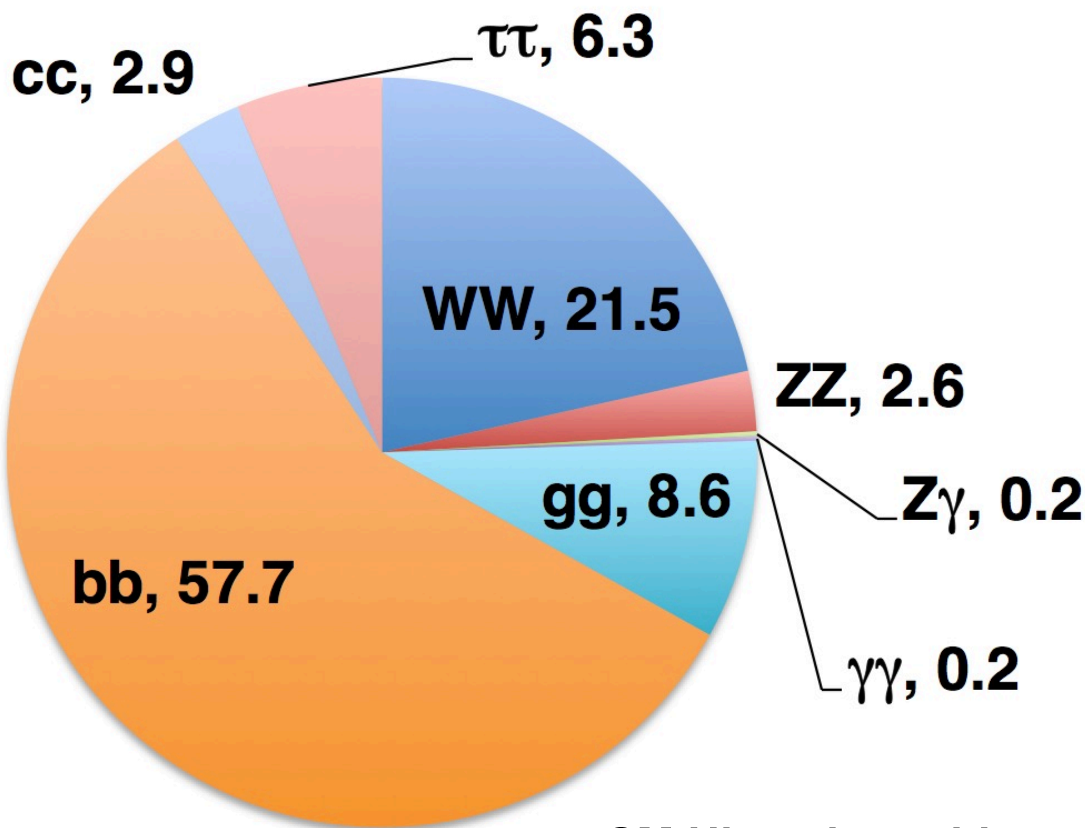






… and decay

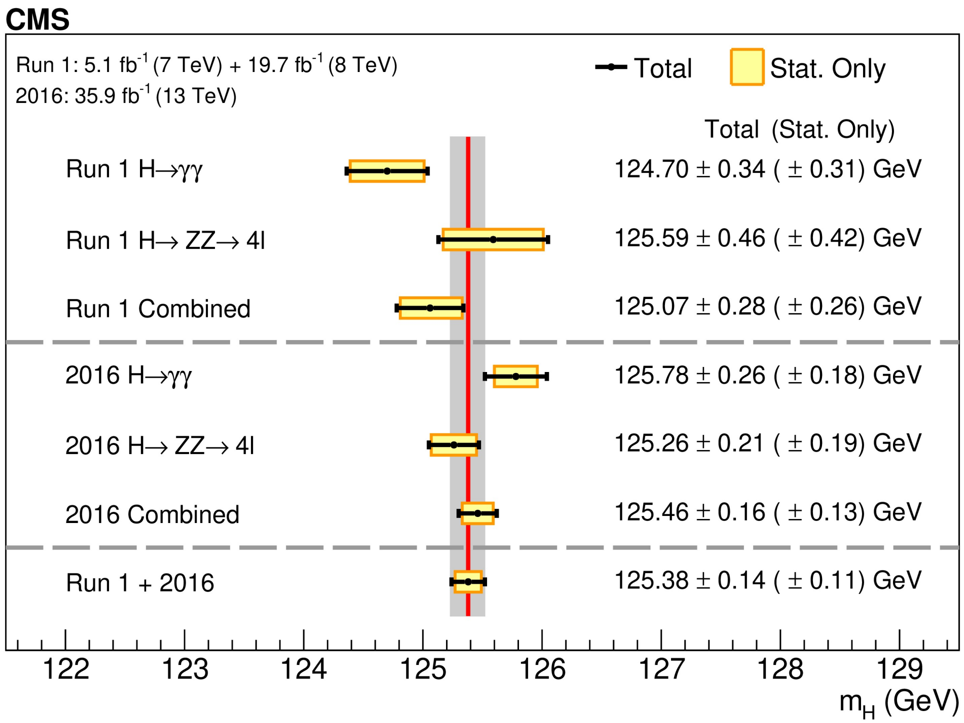
Branching ratio = Probability for Higgs boson to decay to given final state



SM Higgs branching ratios, in %

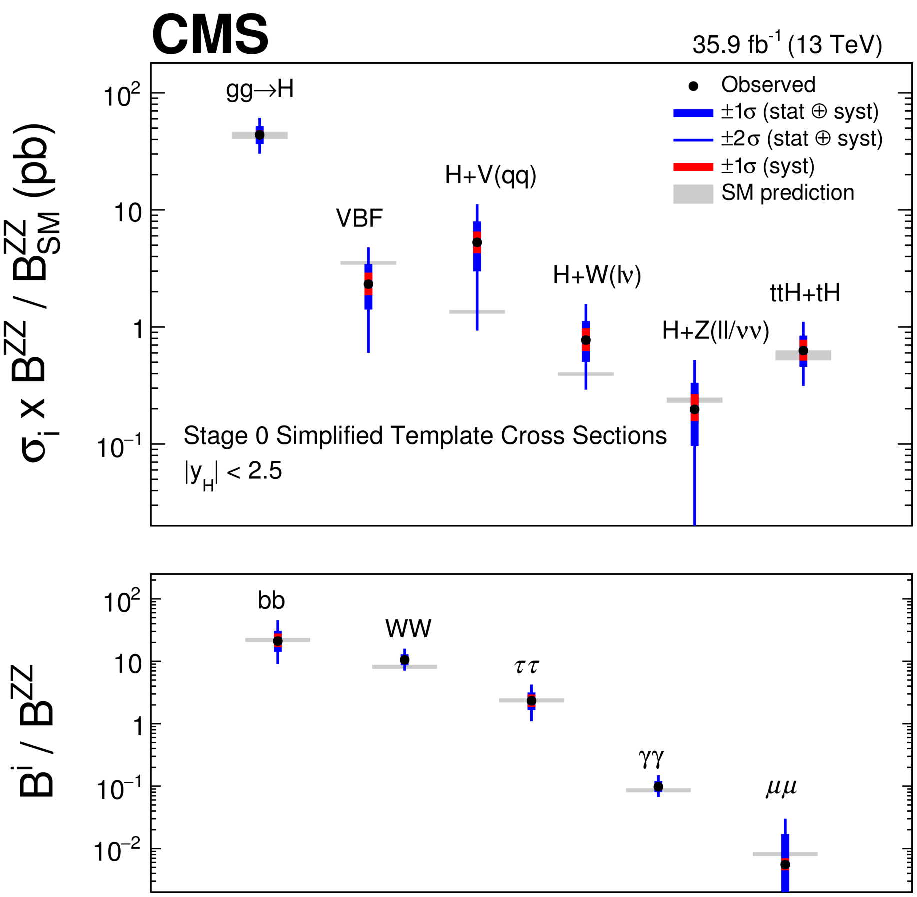
Much of the project of Run 1 and Run 2 has been filling in the picture across these production and decay modes

Run 2: H boson studies mature



- Mass measurement converging

[Phys. Lett. B 805 (2020) 135425]

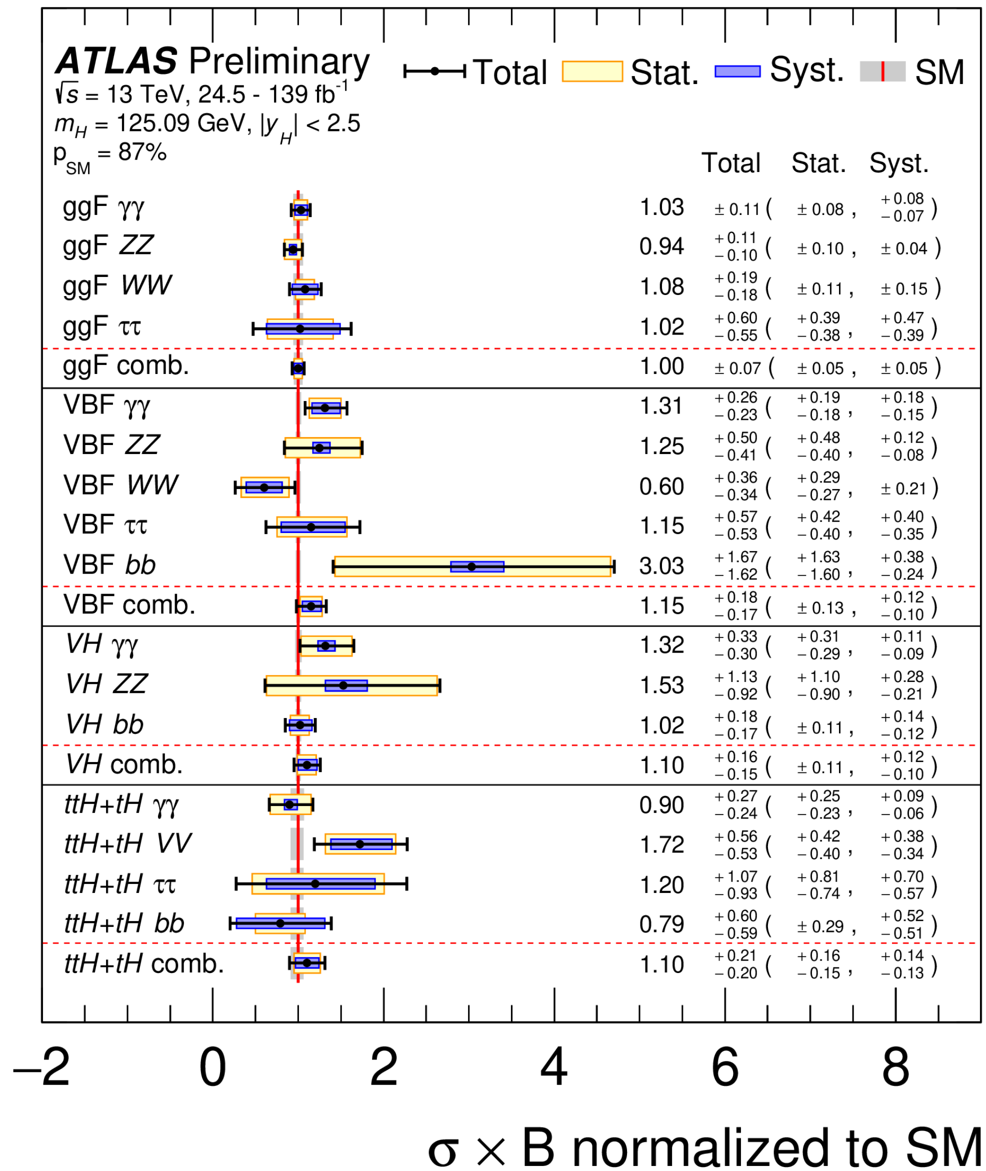


- Simplified template cross sections reduce theory uncertainties by normalizing to specified fiducial region

[Eur. Phys. J. C 79 (2019) 421]

Run 2: H boson studies mature

- Best individual results approaching 10% precision
  - → *Becoming systematics limited*
- Simplified Template Cross Section interpretations as well
  - → *Details in [ATLAS-CONF-2020-053]*
- 6.3σ observation of Wh production (5.2σ expected)



[ATLAS-CONF-2020-027]

In this talk

- Full suite of Run 2 measurements in progress
- **Much recent work points to a new phase in our engagement with the Higgs boson data**

→ *Rare processes*

- kinematic tails, unusual signatures

→ *Detailed study of interaction vertices*

- CP & polarization

→ *Closing in on 2^{nd} generation fermions*

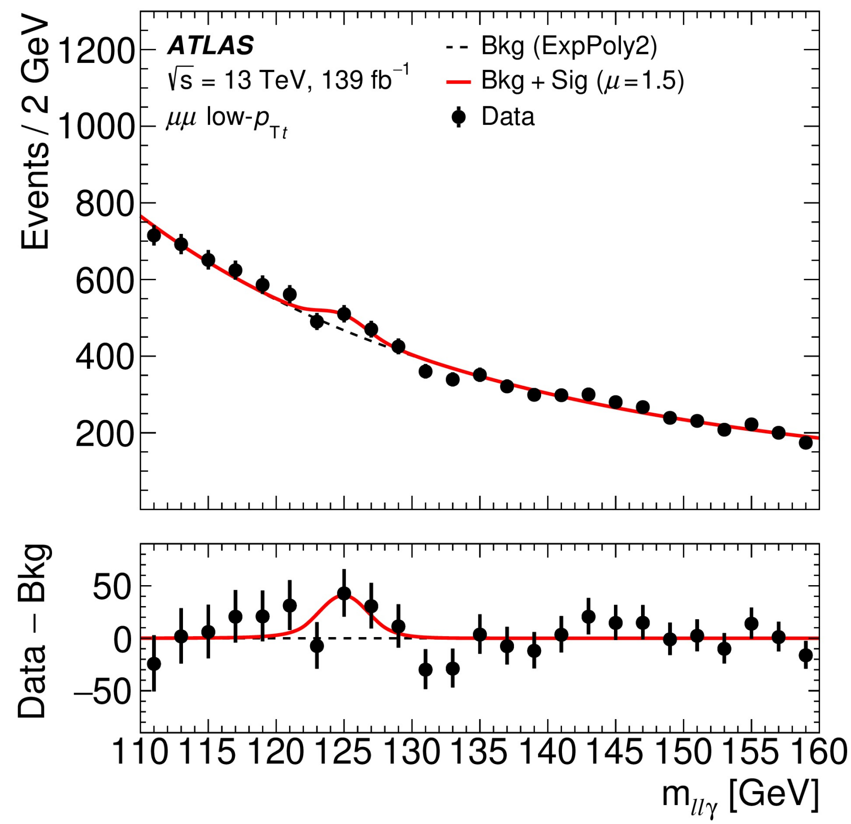
- Evidence for h → $\mu\mu$, searches for h → cc

- Cannot hope to do justice to the body of work that exists
- Aspire to give a flavor of what is compelling and illuminate the path forward

ATLAS h → $\ell\ell\gamma$ Evidence

- **Low-mass**: $m_{\ell\ell} < 30$ GeV, so γ^*, not Z, is dominant
- Categorization by final state lepton flavor (electron or muon), pTt, VBF tag (if present)

  → *pTt is "strongly correlated with the transverse momentum of the llγ system, but has better experimental resolution"*
- Dedicated treatment of overlapping calorimeter showers from eeγ for low mass



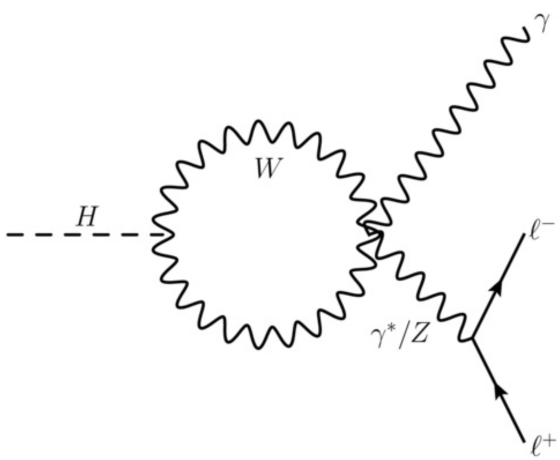
ATLAS HIGG-2018-43,
[Phys. Lett. B 819 (2021) 136412]

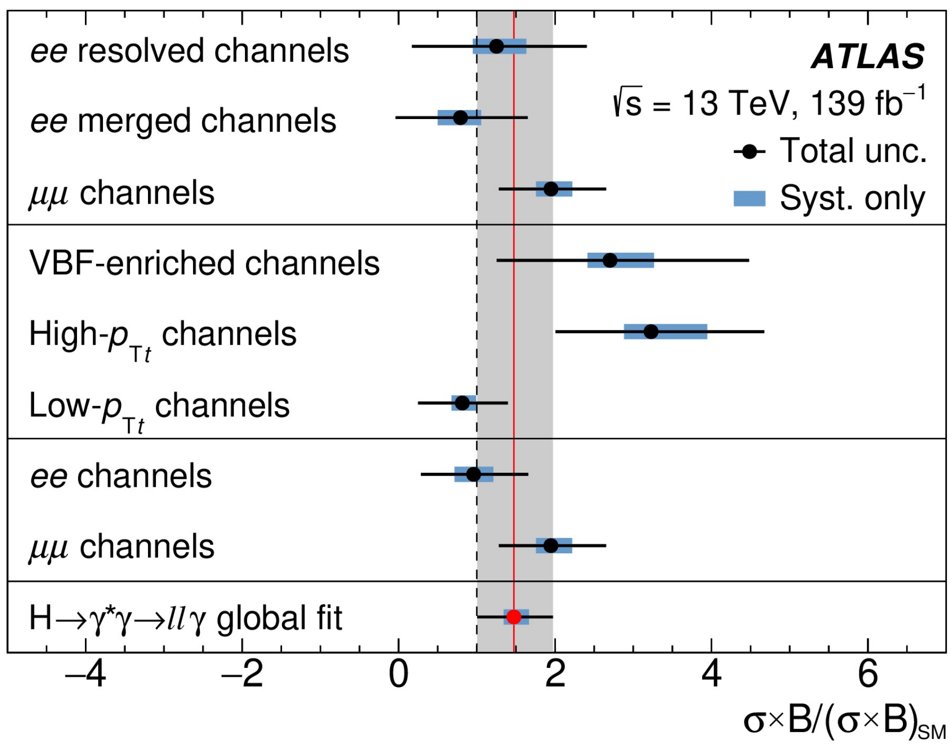
Most sensitive channel

ATLAS h → ℓℓγ Evidence

- **Low-mass**: $m_{\ell\ell} < 30$ GeV, so γ^*, not Z, is dominant
- Categorization by final state lepton flavor (electron or muon), pTt, VBF tag (if present)

3.2 σ observed, 2.1 σ expected

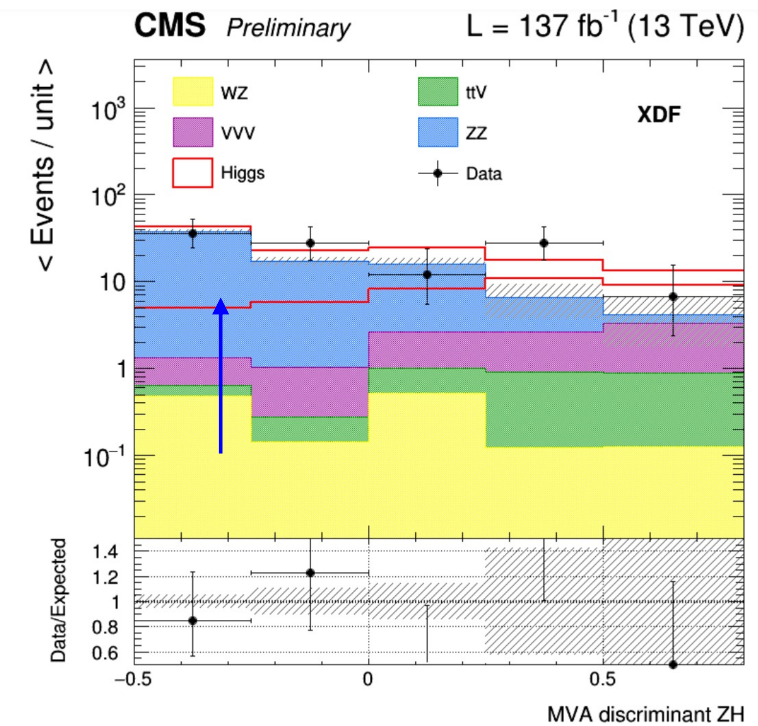




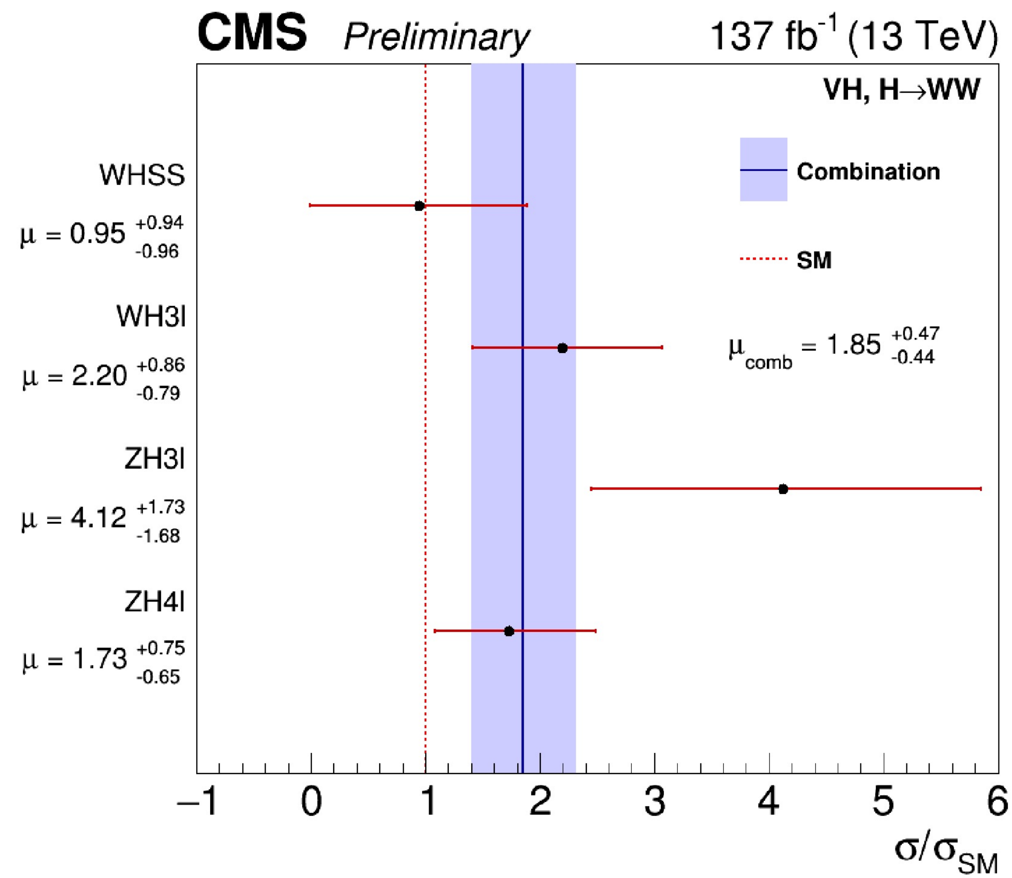
ATLAS HIGG-2018-43,
[Phys. Lett. B 819 (2021) 136412]

CMS Vh, h → WW

- Associated production modes more powerful as datasets grow
- Reintroduced channel $Z \to \ell\ell$ and $WW \to \ell\nu qq$ (done in Run 1)
- New channel with same-sign dileptons (similar done in ATLAS Run 1 measurement)



most sensitive: $Z \to \ell\ell$ and $WW \to \ell\nu\ell\nu$

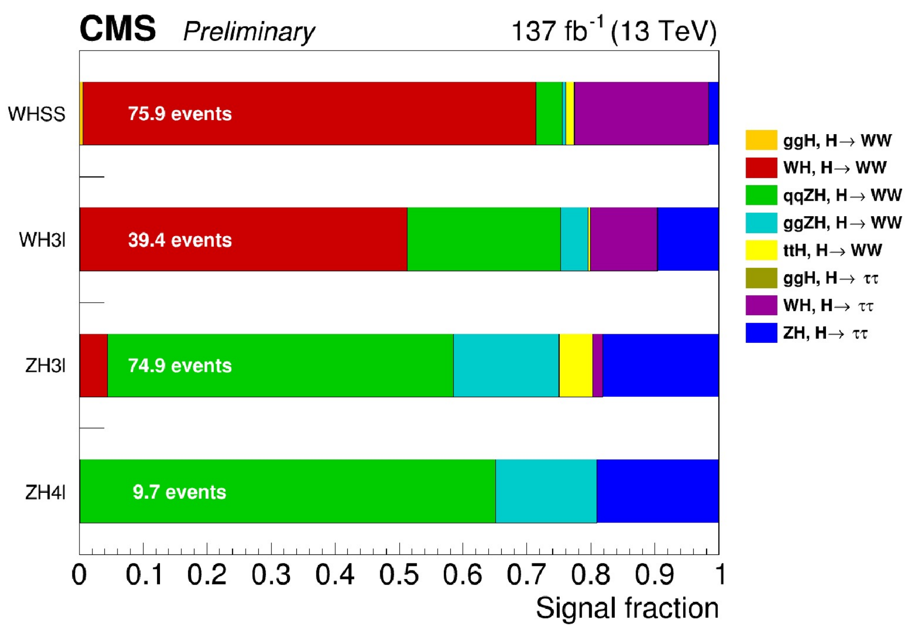


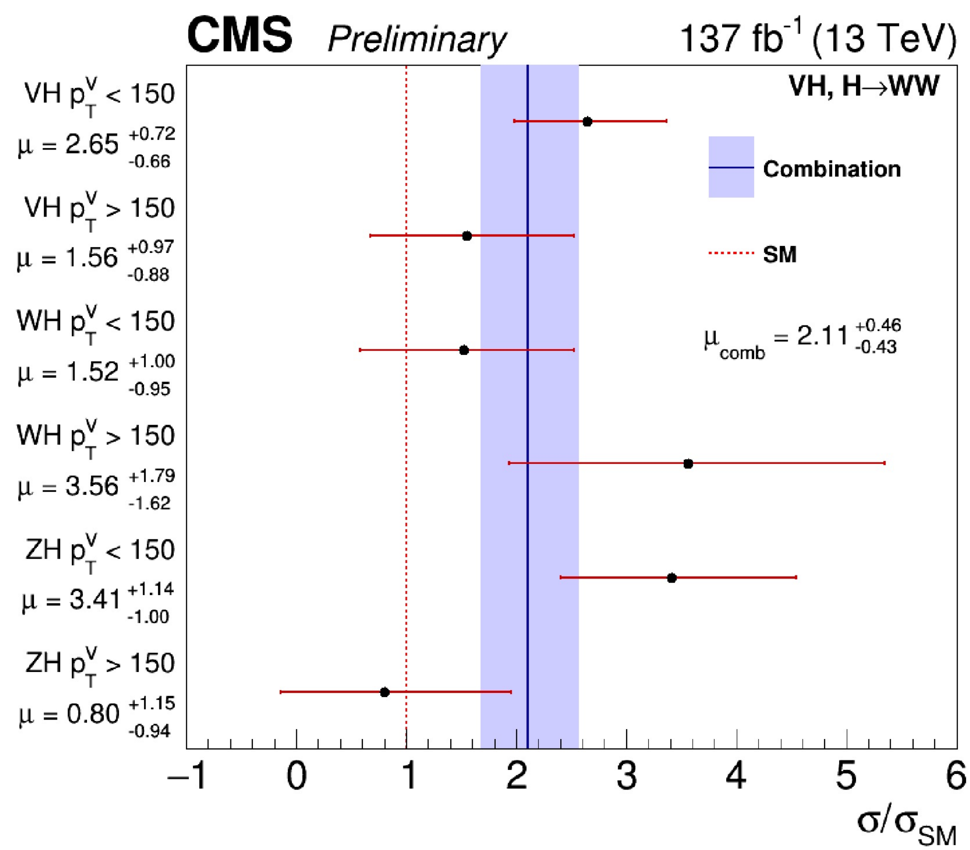
CMS-PAS-HIG-19-017

CMS Vh, h → WW

- Associated production modes becoming more powerful with larger datasets
- Sensitivity to new physics in tails of momentum distribution

→ *parameterize in* Simplified Template Cross Sections

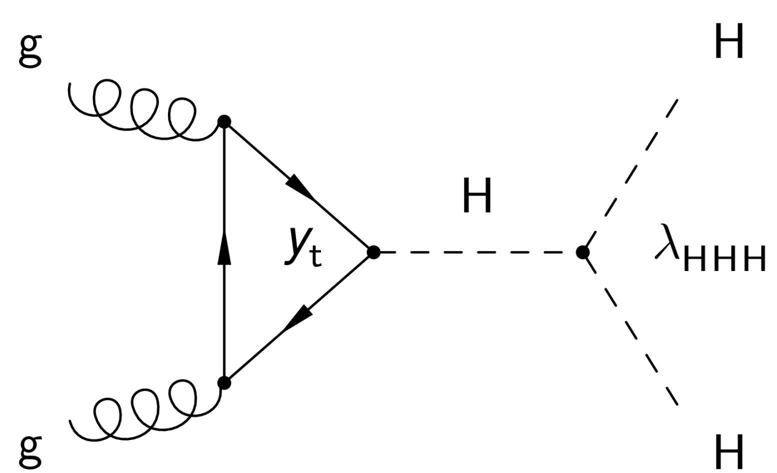


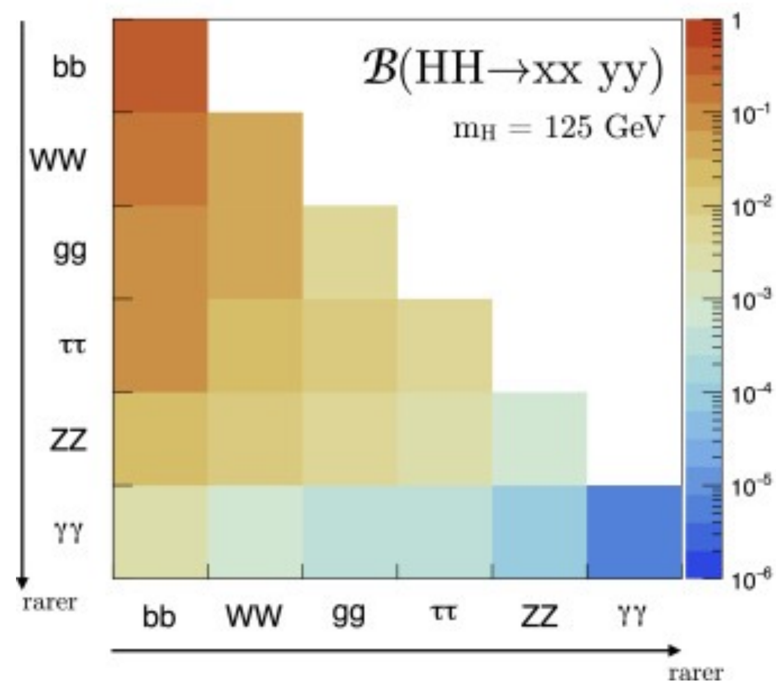


[CMS-PAS-HIG-19-017]

Higgs boson pair production

- Triple-Higgs-boson coupling λ is a fundamental parameter of the Standard Model
- Measuring the shape of the scalar potential
- Connection to electroweak baryogenesis
- Plethora of final states

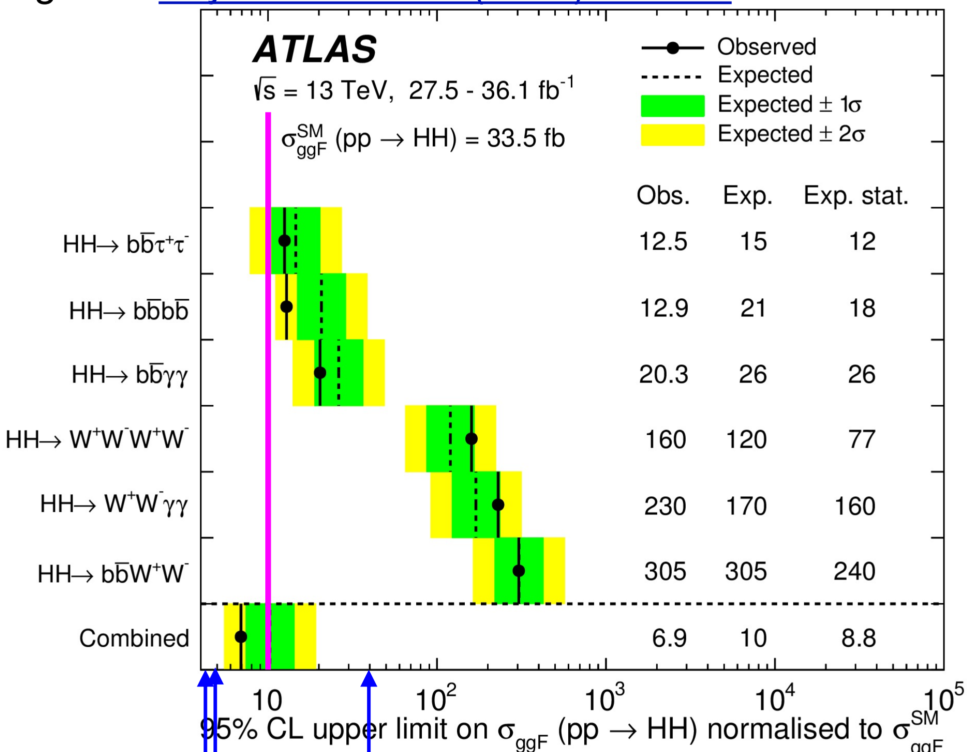


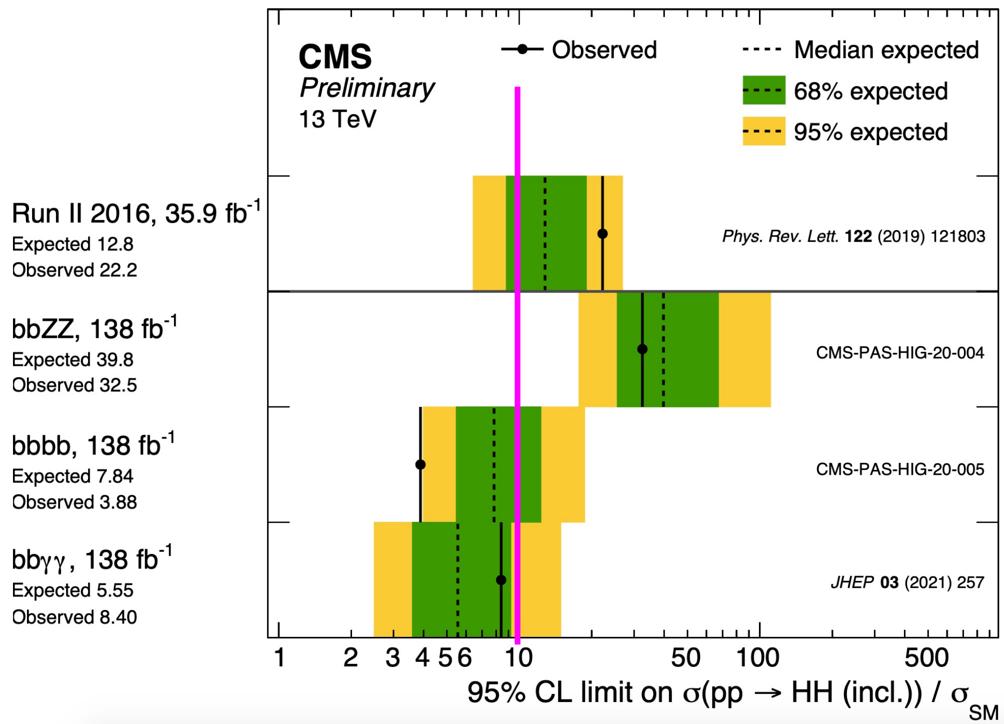


[Reviews in Physics Vol. 5, Nov. 2020, 100039]

diHiggs status

Fig from Phys. Lett. B 800 (2020) 135103





40 (observed) $hh \to WWbb \to \ell\nu\ell\nu$ full Run 2, Phys. Lett. B 801 (2020) 135145

lines at σ/σ_{SM} = 10

4.7 (observed)

$hh \to bb\tau\tau$ full Run 2, ATLAS-CONF-2021-030

- Big combinations of 2016 data
- **Full Run 2 measurements are starting to fill in**

4.1 (observed)

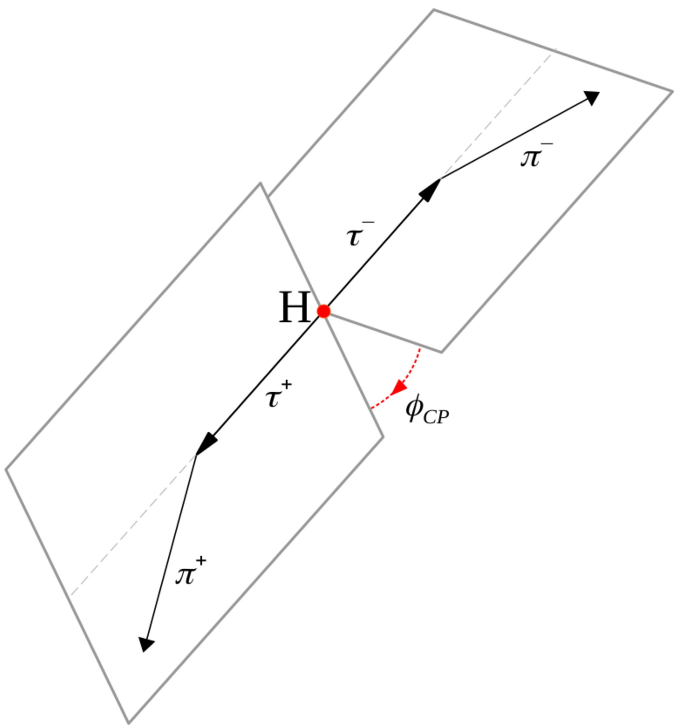
$hh \to bb\gamma\gamma$ full Run 2, ATLAS-CONF-2021-016

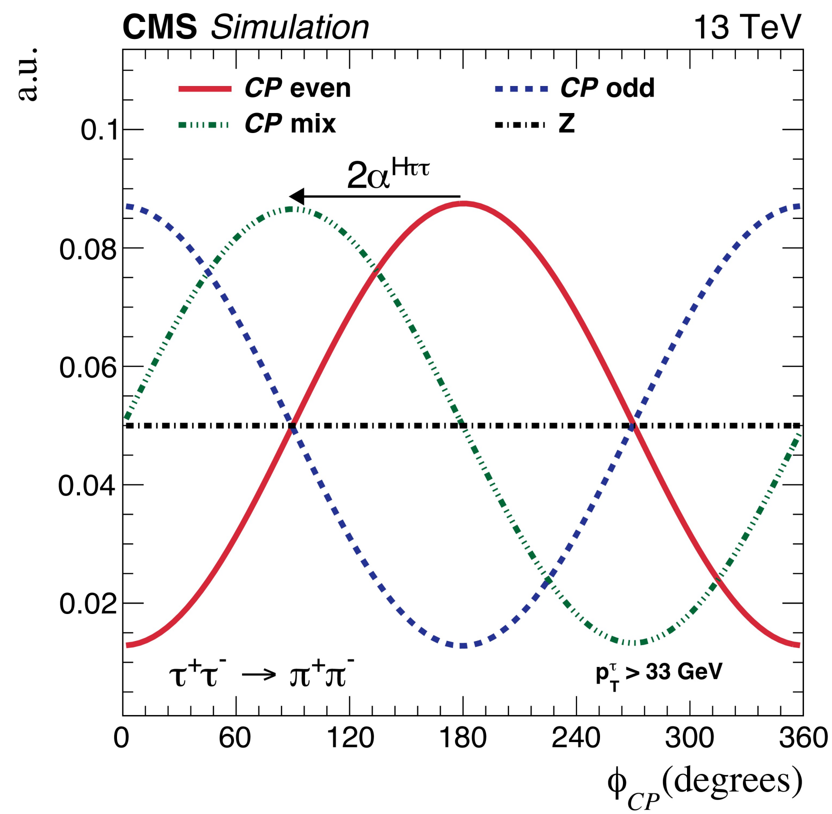
CP violation

- What is it?
  → *Charge conjugation changes sign*
  → *Parity inverts space coordinates $\vec{x} \leftrightarrow -\vec{x}$*
- CP quantum number is a property of a particle, CP violation is the property of a process
- Why do we care?
  → *Sakharov criteria for baryogenesis*
    - First-order phase transition (interactions out of thermal equilibrium)
    - Baryon number violation
    - **C and CP violation**
- History in particle physics
  → *First observed in kaon particle-antiparticle oscillations in 1964*
  → *Studied in b-quarks at BaBar and Belle*
    - CP violation in CKM matrix established, *but not enough to manage baryogenesis*

CMS h → ττ Yukawa CP

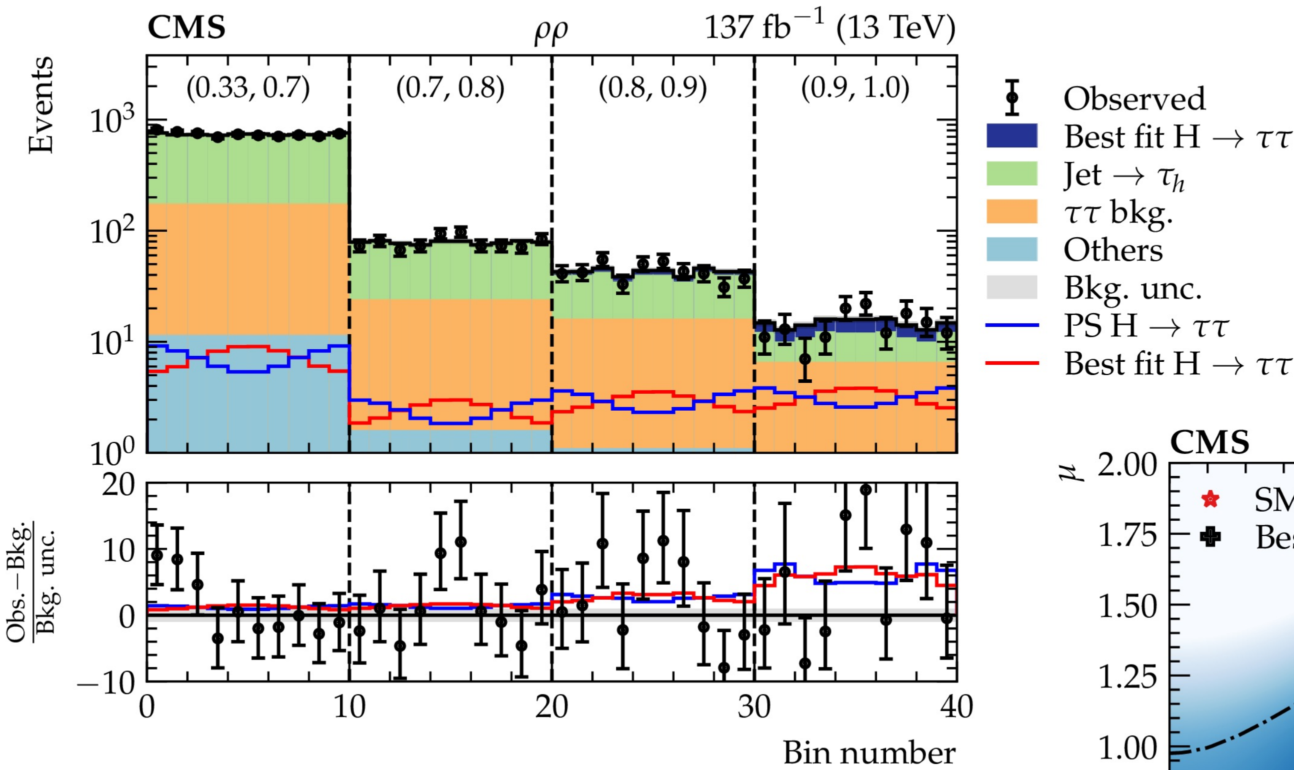
- CP violation in the couplings of h would be direct sign of new physics
  → *Extensively studied in gauge boson sectors, but more plausible (may occur at tree level) in couplings to fermions*
- parameterize via $\alpha^{H\tau\tau}$, 0 degrees in SM
  → *as large as 27 degrees in nMSSM*
- Full Run 2



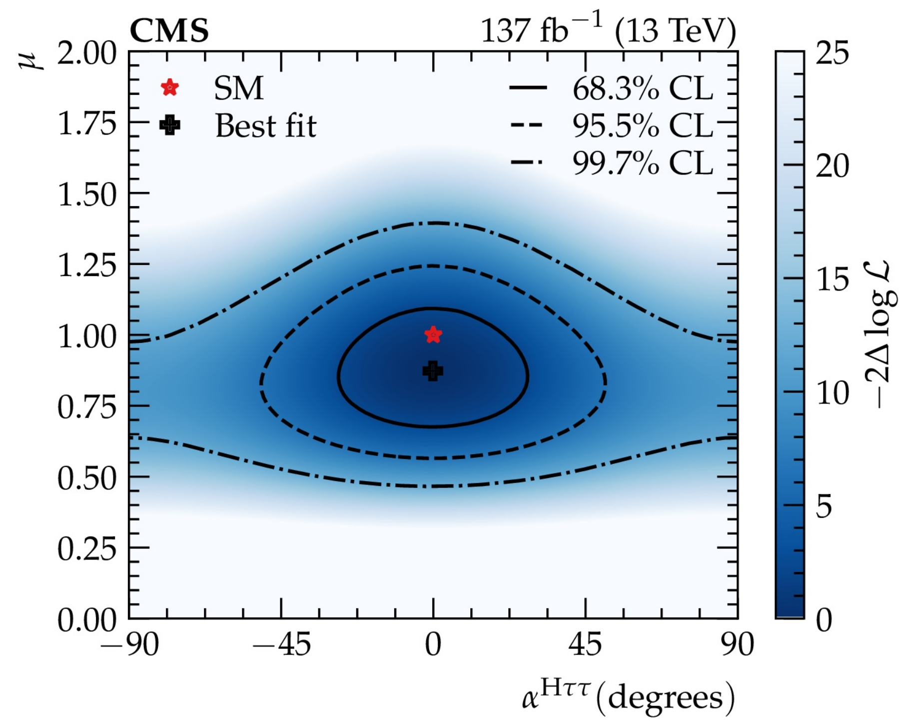


CMS-HIG-20-006, submitted to JHEP

CMS h → ττ Yukawa CP

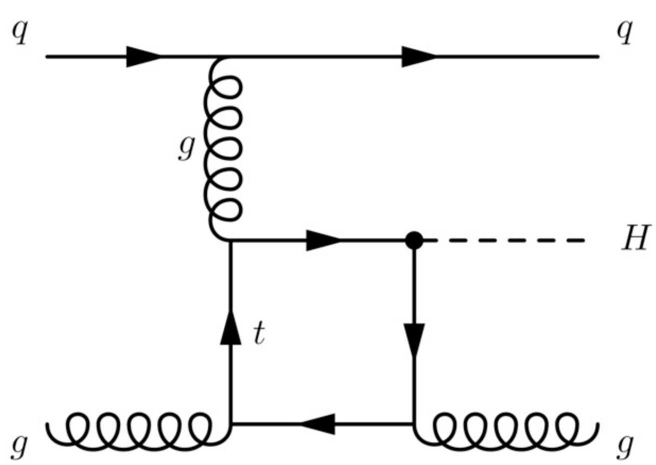


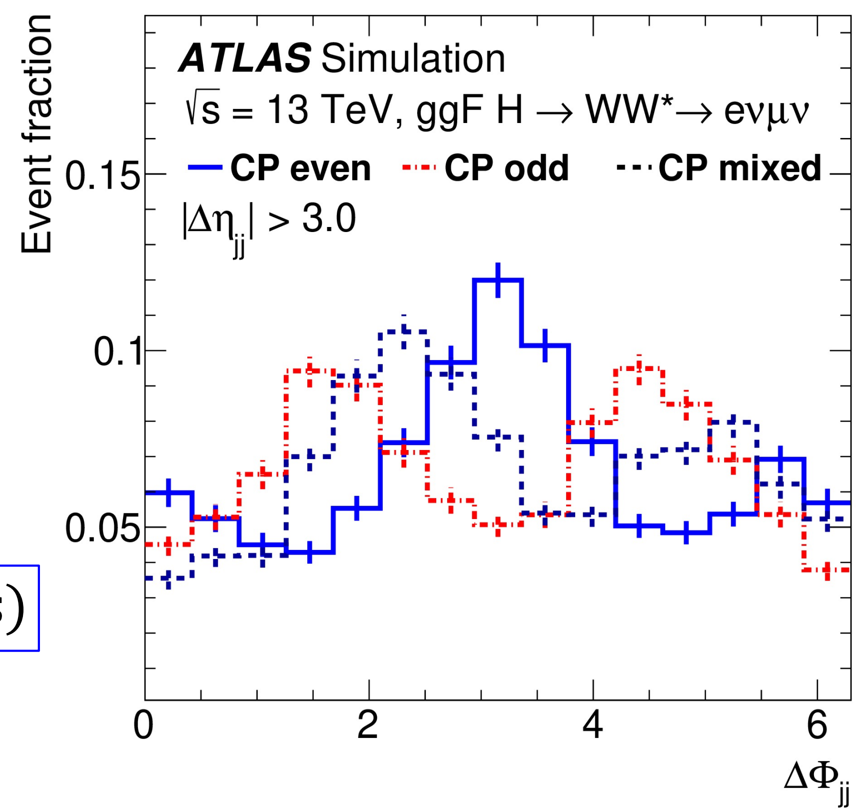
Most sensitive category reconstructs τ through intermediate ρ resonance



ATLAS h → WW CP: ggH

- Spin and parity of H[125] established: J^P =0+
- Mixing, CP-odd couplings, also well-constrained
- Study interference of **CP-even and CP-odd coupling to gluons** in ggH + 2 jet events





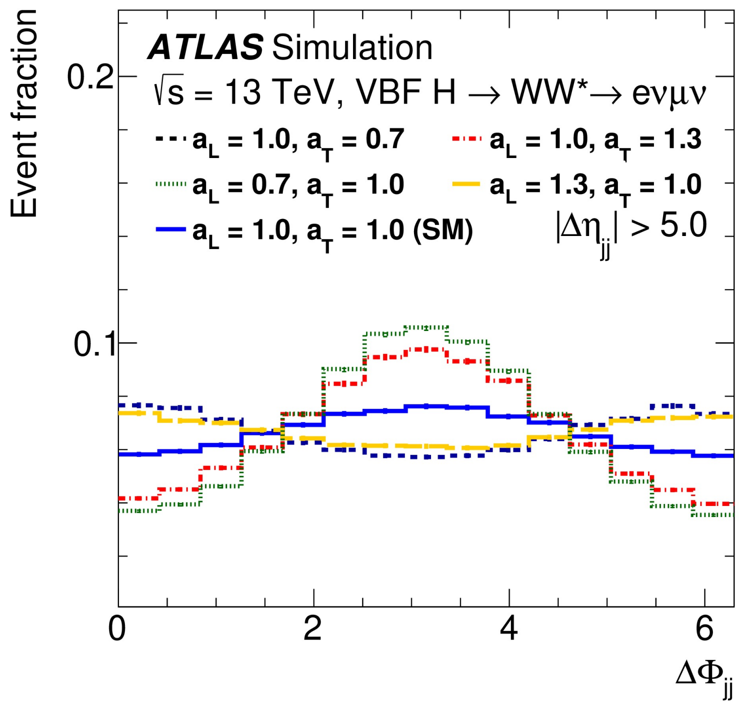
$$\tan(\alpha) = 0.0 \pm 0.4\ (\text{stat}) \pm 0.3\ (\text{sys})$$

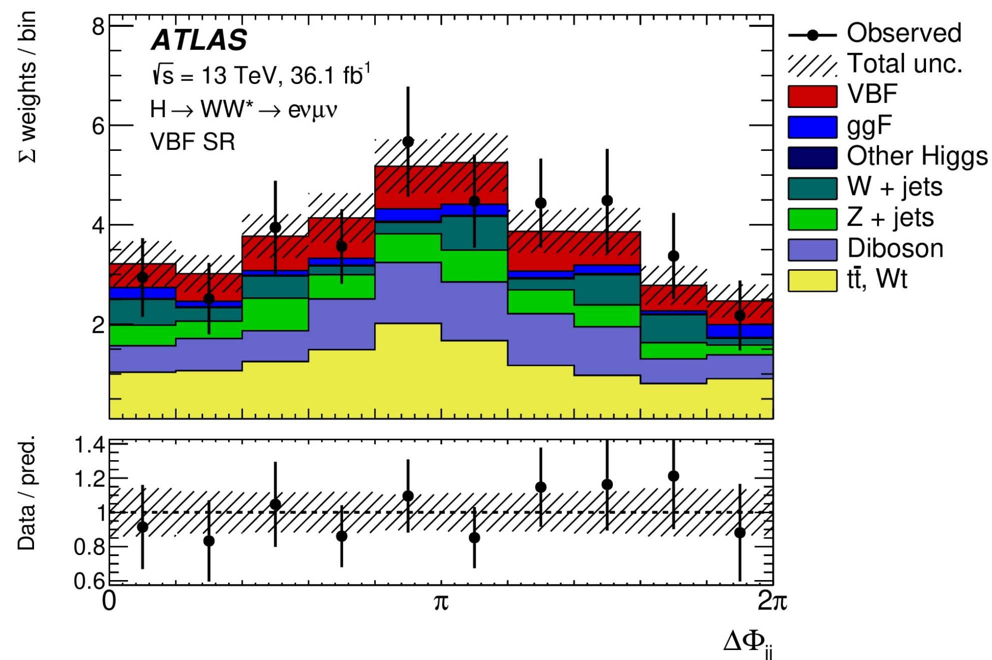
SM value = 0

HIGG-2017-13, submitted to EPJC

ATLAS $h \to WW$ CP: VBF

- Focus on H+2j production: VBF production separating coupling to longitudinally and transversely polarized vector bosons





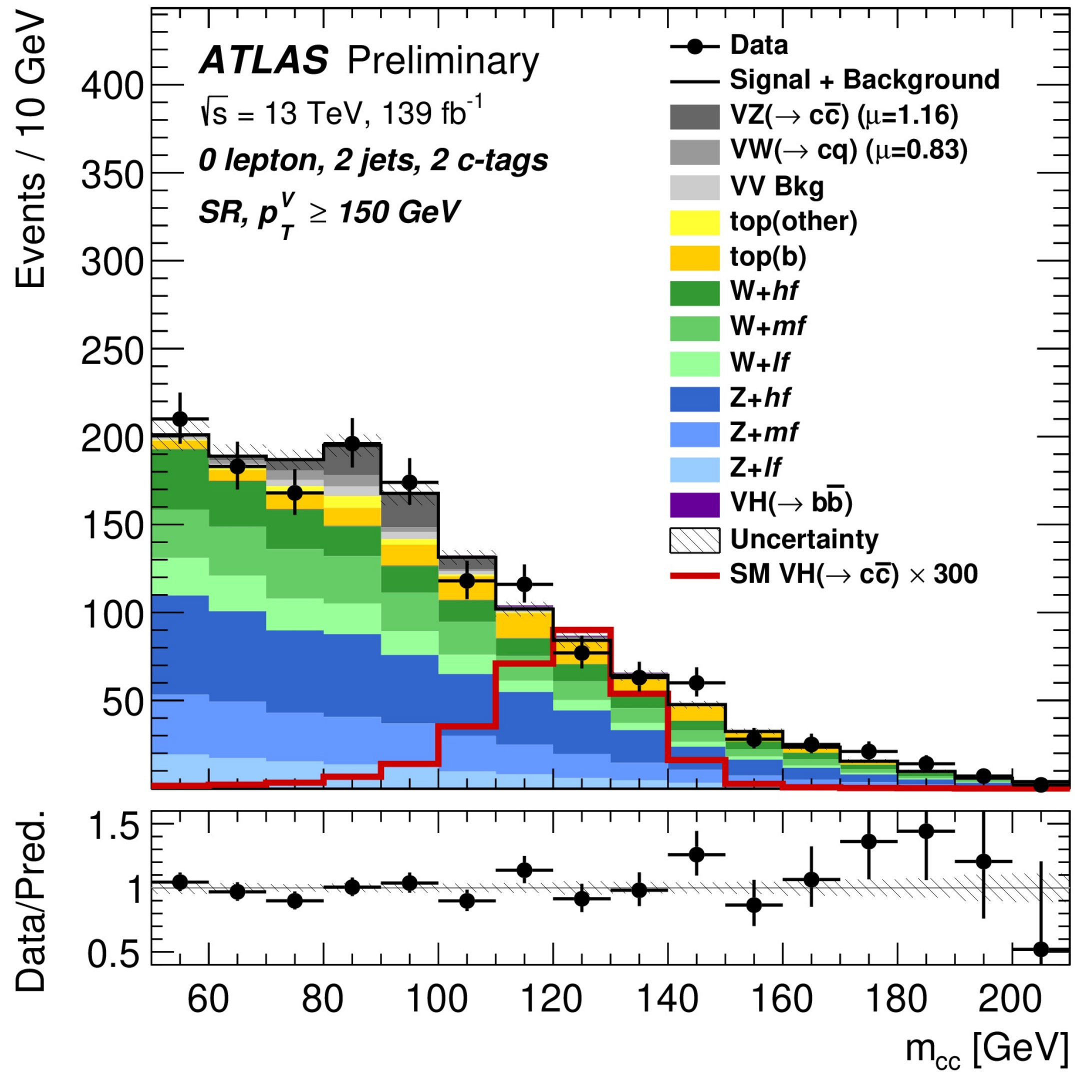
	expected	observed
a_L shape + rate fit (a_T profiled)	$1.00^{+0.08}_{-0.10}$(stat.)$^{+0.08}_{-0.13}$(syst.)	$0.91^{+0.10}_{-0.18}$(stat.)$^{+0.09}_{-0.17}$(syst.)
a_T shape + rate fit (a_L profiled)	$1.0^{+0.4}_{-0.5}$(stat.)$^{+0.2}_{-0.4}$(syst.)	1.2 ± 0.4(stat.)$^{+0.2}_{-0.3}$(syst.)

HIGG-2017-13, submitted to EPJC

ATLAS h to charm

- 2^{nd} generation quark, branching ratio ~3%
- bottom vs charm: must distinguish by particle lifetimes in jet tagging

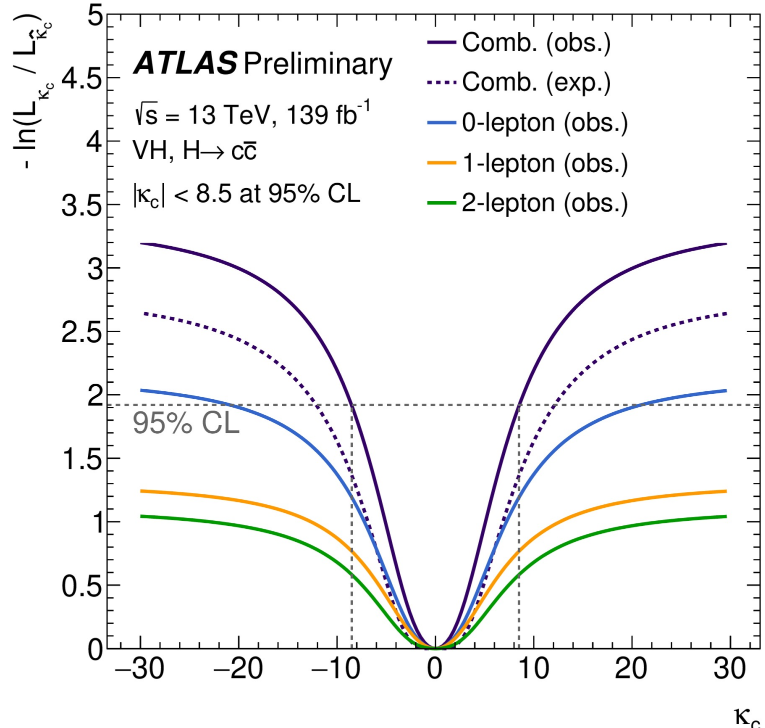
  → *veto b-tagged jets*
- Associated production: categorize by number of charged leptons from W/Z decay
- Categorize by number of charm-tagged jets

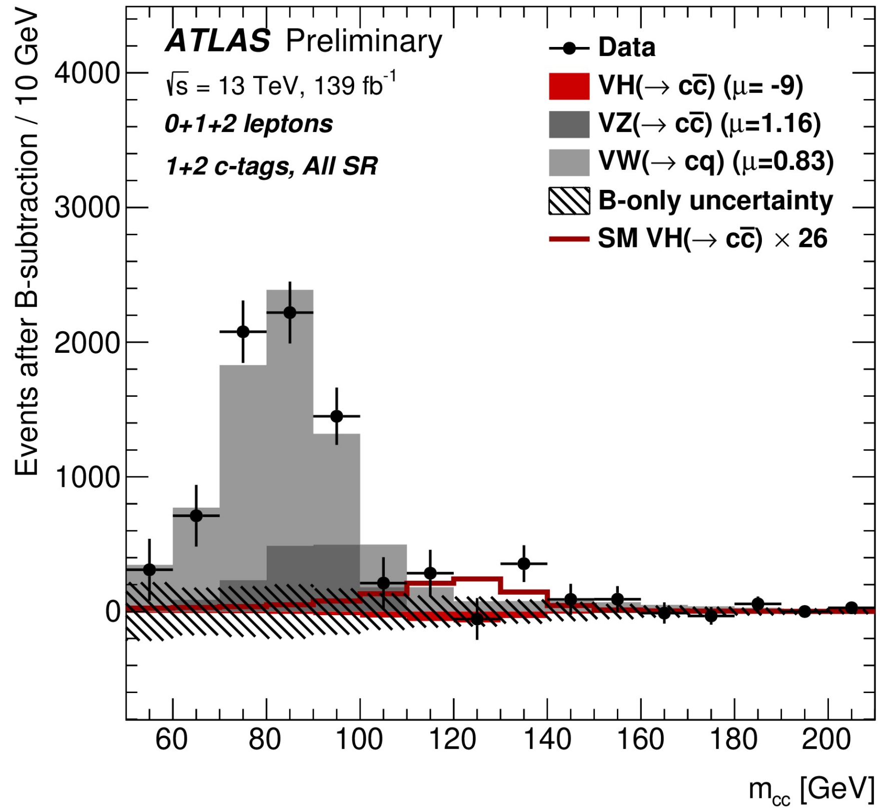


ATLAS-CONF-2021-021

ATLAS h to charm

- Confirm results using W, Z decays containing charm



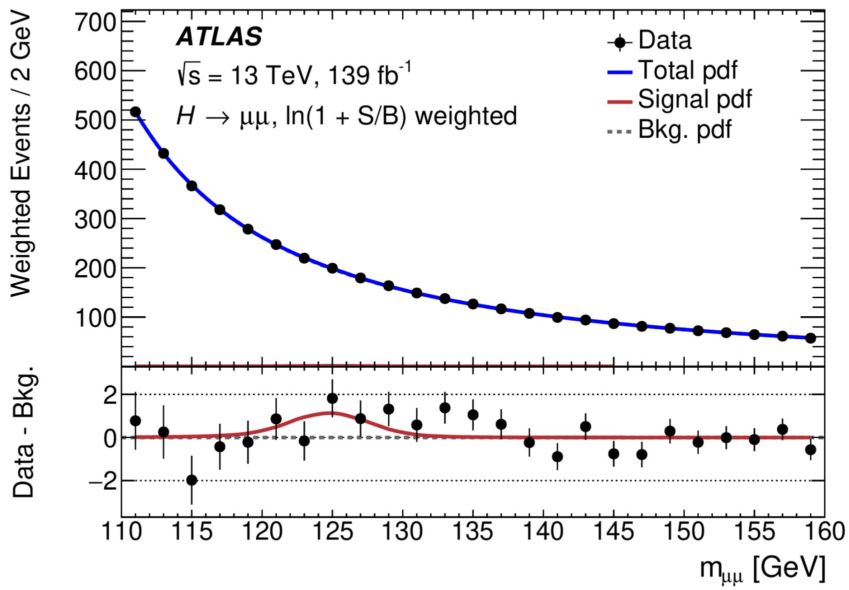


26 x σ_{SM} x BF observed

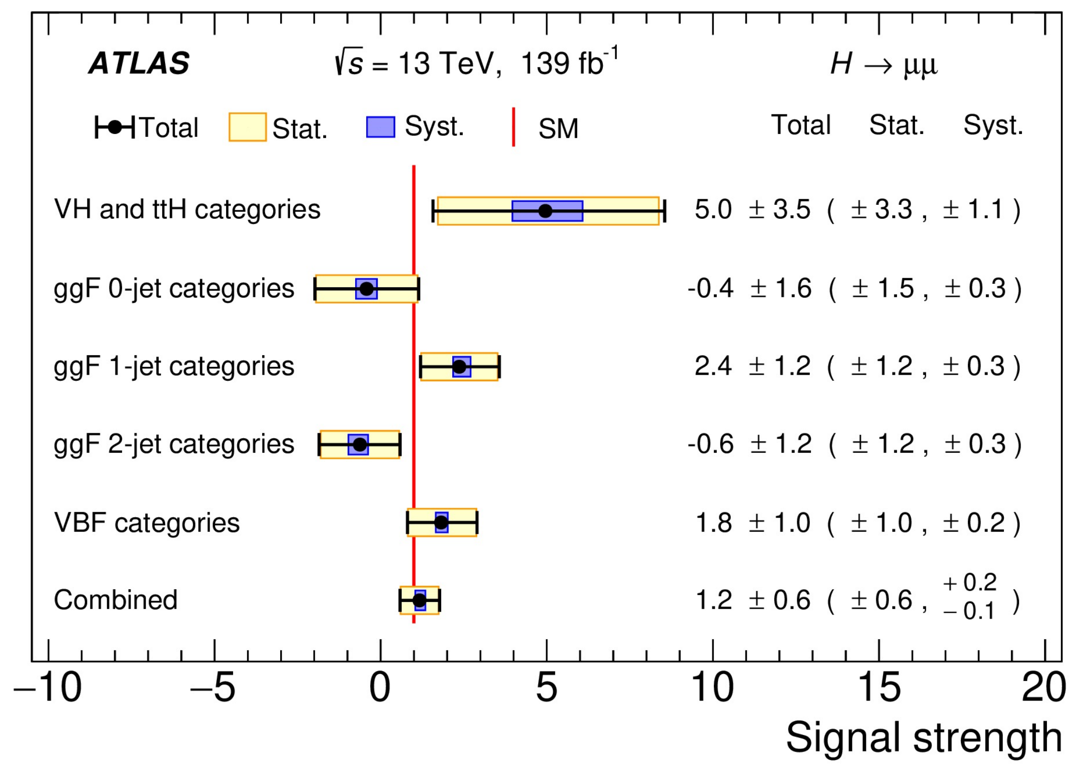
31 x σ_{SM} x BF expected

ATLAS-CONF-2021-021

ATLAS h → μμ Search



- h → μμ a deceptively simple target
- SM BR (2.17 ± 0.04) × 10^{-4}
- FSR recovery
- Categorized in ggF, VBF, VH, ttH

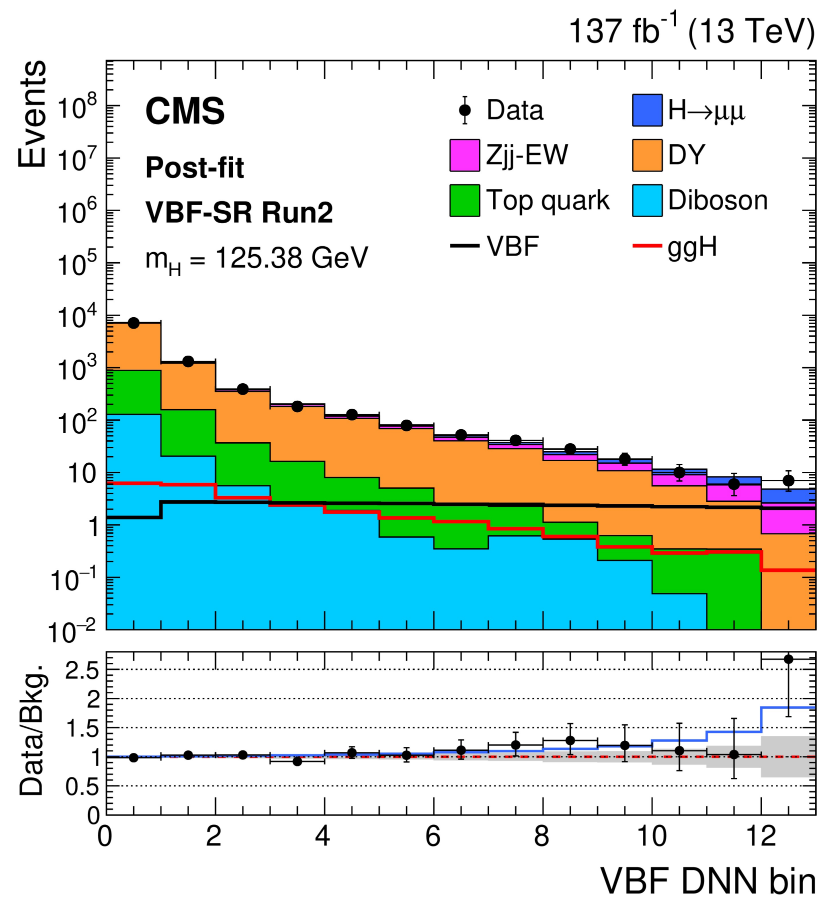


Run 2:
Observed 2.0 σ
Expected 1.7 σ

ATLAS HIGG-2019-14,
[Phys. Lett. B 812 (2021) 135980]

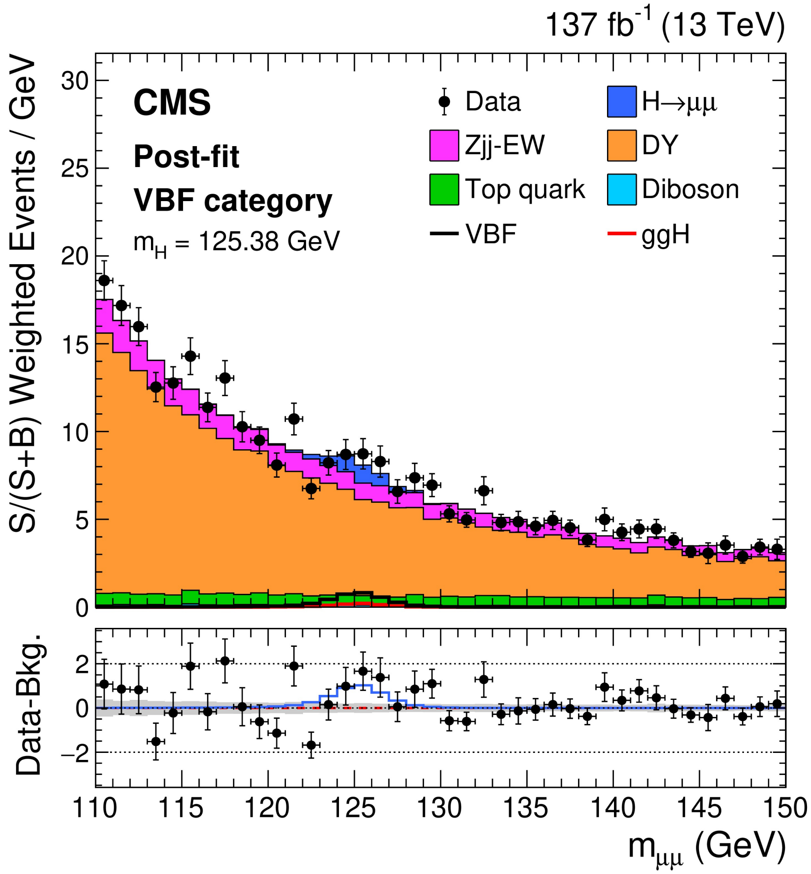
CMS h → μμ Evidence

- Categorized in ggF, VBF, VH, ttH
- Run 1 + Run 2, combined
  - → *Run 1 adds 1%*
- FSR photon recovery
- VBF most sensitive category
  - → *DNN incorporates $m_{\mu\mu}$, $\Delta\eta(\mu\mu)$, quark-gluon jet discriminant, + others*
  - → *Sidebands still defined by $m_{\mu\mu}$, with SR: $115 < m_{\mu\mu} < 135$ GeV*
    - Background not purely data-driven: sensitivity improved by having MC models, since would be stats limited in high-purity categories with small event yields

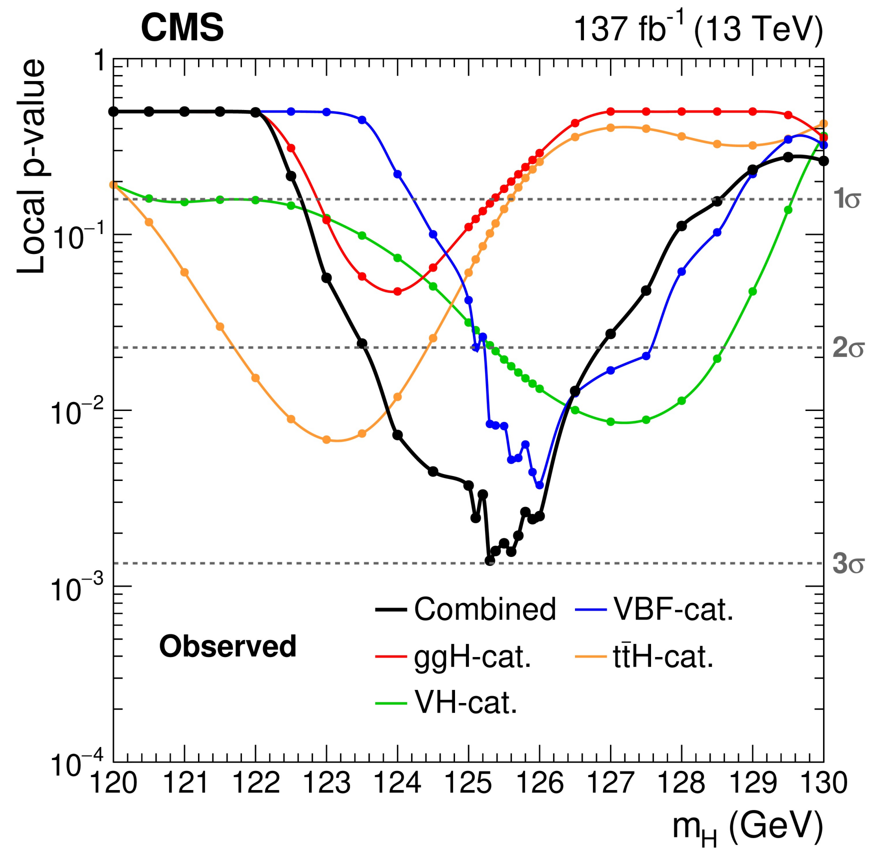


CMS-HIG-19-006, [JHEP 01 (2021) 148]

CMS h → μμ Evidence



Observed 3.0 σ (expected 2.5 σ)



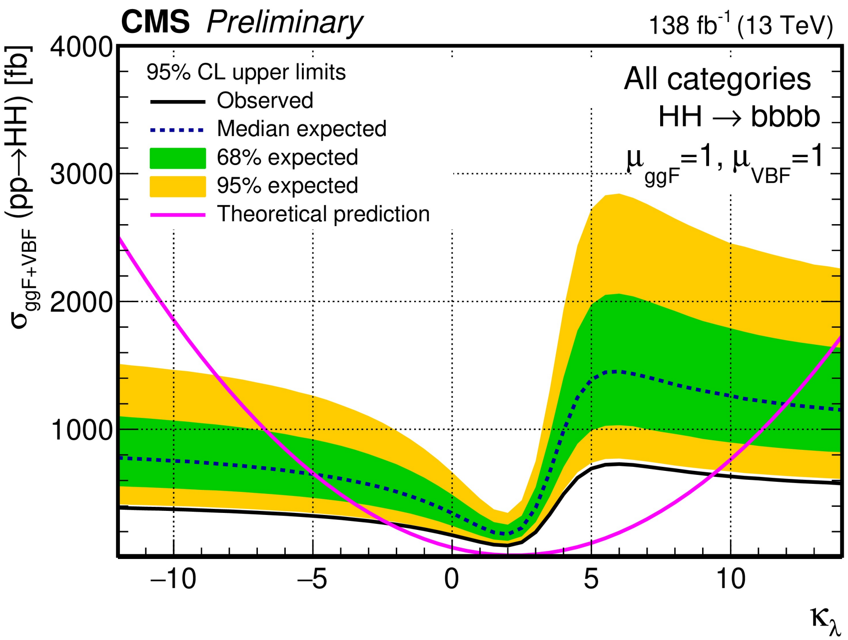
$$\hat{\mu} = 1.19\ ^{+0.40}_{-0.39}\ (\text{stat})\ ^{+0.15}_{-0.14}\ (\text{sys})$$

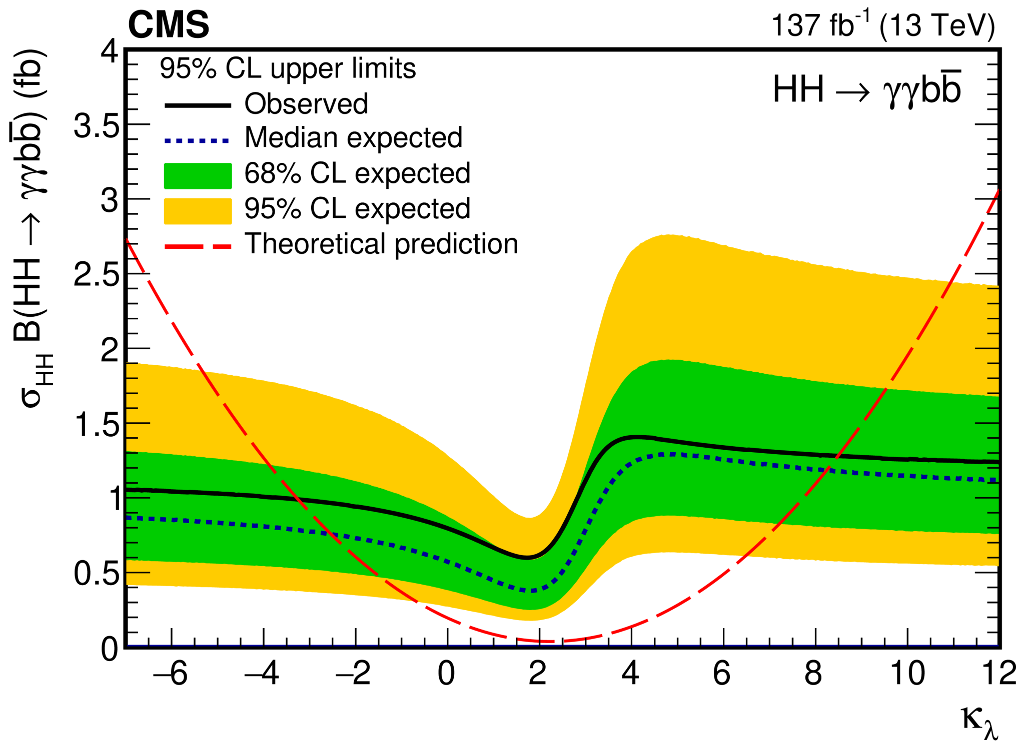
Conclusions

- Run 2 yielding a comprehensive picture of the observed Higgs boson
  → *Analyses moving to a new phase as increased datasets and analysis sophistication give access to new signatures*
- Run 3 to start in Spring 2022
  → *CMS magnet on at full strength last week*
- High-luminosity LHC coming up in 2027
- Deep connection to possible BSM physics makes this a compelling area for continued investigation
  → *Have emphasized connection to baryogenesis through modified couplings*
  → *Interactions/connections to dark matter*
  → *Direct BSM searches*

backup

CMS hh → 4b, bbγγ





HL-LHC overview

- Start of the high-luminosity LHC (HL-LHC) in 2027 will be the culmination of over a decade of intensive work
- 14 TeV proton-proton collisions, **3000-4000** fb^{-1} at instantaneous luminosity of 2×10^{35} $cm^{-1}s^{-1}$
- Comparison: Run 3 imminent at 13 TeV (possible upgrade to 14 TeV), **300-350** fb^{-1} and inst lumi up to 2×10^{34} $cm^{-1}s^{-1}$
- Up to 140-200 interactions per bunch crossing